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Real-time Algorithm for Detection of Breakthrough Bone Drilling

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Abstract

The purpose of this study is to develop a force control algorithm that detects breakthrough of drill bit during bone drilling process, where the drilling process will halt and return to a safe position once the algorithm is triggered. Orthopaedic surgery in traditional practices does not equipped with any means of detection method to detect the breakthrough in drilling process. It mostly depends on the surgeon's experience and skills when conducted the operation. The algorithm is built using Simulink model under Matlab software and implemented on WinCon software to run under real-time process. The breakthrough algorithm detects the differences of sharp drop force in z-direction and calibrates the force in tri-axial direction as the threshold value. The system is verified through an experiment drilling cow femur bone using 5 DoF CRS Catalyst-5 robots. Preliminary drilling test is conducted to observe the sharp drop in the force value which is to be the threshold force. This will help to increase the safety enhancement during drilling process cause by drill bit breakage, unnecessary drill bit breakthrough, excessive heat generation, and mechanical damage to the bones caused by uncontrolled and large forces.

Keywords: Bone drilling, Robotic assisted surgery, Breakthrough control algorithm

Nomenclature

F_x	force in x-direction
F_y	force in y-direction
F_z	force in z-direction
F_t	threshold force
v	velocity of CRS Catalyst-5 robot
a	acceleration of CRS Catalyst-5 robot
x_i	initial position of CRS Catalyst-5 robot
x_d	desired position of CRS Catalyst-5 robot

1. Introduction

Bone drilling process is a common operation in traditional and modern surgery practice for medical applications. The operation, known as orthopaedic surgery, involves treatment of bone fracture using internal fixation method.

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Traditional practice uses a hand-held motor driven tool to perform the drilling process and depends only on the surgeon's experience and skills during the operation to control the penetration of the drill bit. It is not equipped with any detection method to detect the crossing of interfaces between hard and soft tissues and to discriminate the layers of tissues [1]. For today's modern surgery practice, automated machine or robot assisted surgery uses several parameters to control the operation and these parameters are forces and torques, feed rate and cutting speed. As reported by Wen-Yo Lee et al. [2], high pass filter thrust force signal is used when drilling porcine scapula neck and porcine skull to detect the interfaces between bone layers and breakthrough the penetration of the drill bit. It also includes two more signals which are the drilling torque and feed rate trend to help the breakthrough point.

A real-time breakthrough detection technique based on force derivatives was also presented by Alotta et al. [3], who carried out experiment using an Instron Testing Machine equipped with a 1 to 1000 N range load cell to drill a swine femur. Marouf et al. [4] developed a breakthrough control system based on a modified Kalman filter to detect the force difference between successive samples (FDSS) which was experimented on porcine femoral shafts using a drill feed unit, a bi-directional force sensor, a quick mount drill holder and a compliant bone holder. Past researchers have also applied other methods and techniques for detection of breakthrough.

Y.L. Hsu et al. [5] used an electric current consumed by DC motor analyzed by fuzzy controller as the sensing signal. The voltage dropped from the DC motor indicated the force during the drilling process. Detection methods are important in orthopaedic surgery as a safety enhancement. It can help to prevent drill-bit breakage, unnecessary drill breakthrough, excessive heat generation, and mechanical damage to the bones caused by uncontrolled and large forces [6].

The natural and unique properties of bone are the key to the detection method developed in modern practice. This is because at macrostructure level, the bone can be distinguished into two major types, cortical (or compact) and cancellous (or trabecular) [7]. The structure of bone is built with cortical bone wrapping around the struts of cancellous bone. The cortical bone lies outside of the surface and acts as a protective shell for cancellous bone. Cortical bone has a much higher density with low surface area from cancellous bone, but it has a degree of porosity in the bone itself [8]. In this paper, a detection method based on Proportional and Derivatives (PD) motion control coupled with force control system in real-time drilling process will be presented. The system is build using Simulink model under the Matlab software environment. An experimental method is presented, followed by the analysis of several results.

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2. Experimental Setup

The set-up of the system to conduct the robotic bone drilling process experiment is illustrated in Figure 1. It consists of the CRS CataLyst-5 robot, C500c controller, Maxon DC motor (model RE 206508), ATI 6 DoF Force-Torque sensor and a holding device [9]. The CRS Catalyst-5 robot uses a 5 DoF articulate joint and a linear track. Each joint of the robot has an incremental encoder to provide continuous information on motor position. C500C controller provides safety circuits, power and motion control for the arm. It drives the motors in each joint, keeps track of motor position through feedback from the encoders, computes trajectories and stores robot applications in the memory [10].

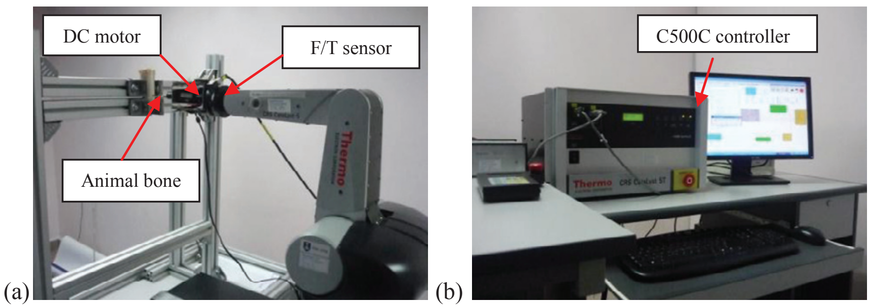


Fig. 1. Experimental setup (a) CRS Catalyst-5 robot (b) C500C controller

The force and torque sensor is mounted directly on the tool flange of the robot arm. The pressure-sensitive devices inside the force sensor will measure the applied forces and torques, and transfers this information to the controller [11]. The speed of the motor or the cutting speed (rpm) is controlled directly from the AC power supply whereas the velocity (mm/s) and the acceleration (mm/s2) of the robot movement along the linear track control the feed rate of the drilling process.

The drilling processes were performed on a fresh bovine femur. The skin and all soft tissues are removed from the femur leaving behind only the naked bone itself. The entire specimens are cut into several parts to ensure that rigid clamping on the holding device. An industrial titanium coated high speed steel (HSS) drill bit of 4mm in diameter was used in the drilling process. The feed rate parameters used in the experiment are tabulated in Table 1. The drill bit cutting speed used in this experiment remained constant at 2000rpm.

Table 1. Feed rates of CRS robot

No.	Feed rates	
	Velocity (mm/s)	Acceleration (mm/s^2)
1	0.05	0.0125
2	0.06	0.015

3. Control Architecture

The force control architecture is design using Matlab Simulink model as shown in figure 2. The model is built up of several subsystems consisting of the CRS takeover, CataLyst-5 Inverse Kinematics, CataLyst-5 Position Controller, Force-Torque Sensor, Force-Torque Sensor Transformation and Detection Force control. The CataLyst-5 Takeover is used to switch between open and closed architecture mode, where the closed architecture mode uses the built-in controllers of the C500C system, whereas for the open architecture, the controller algorithm is designed using Simulink and implemented in the WinCon software. The WinCon generates a real-time code from the Simulink model and targets it on the processor of the PC.

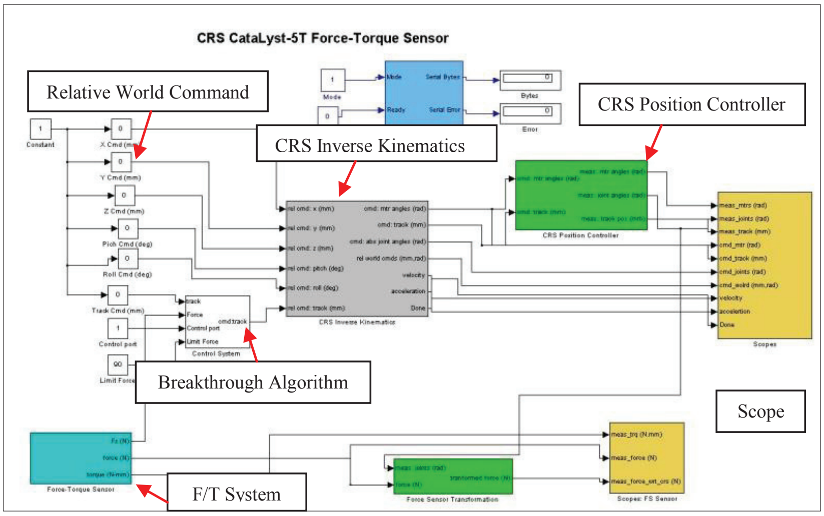


Fig. 2. Force control architecture system

The subsystems for the CataLyst-5 Inverse Kinematics and CataLyst-5 Position Controller together with the Relative World Command are used to control the position of the end-effectors using the world-based coordinate system. Whereas, the CataLyst-5 Position Controller is used to control the position of the robot joints and robot movement on the linear track. The Force-Torque Sensor subsystem measures and calibrates the applied forces and torques and Force-Torque Sensor Transformation transforms the force relative to the world frame. The breakthrough algorithm is created in the Control subsystem. The scope is able to view the forces and torques, commanded and measured motor , joint, track and world coordinate positions [12].

4. Breakthrough Algorithm System

This section will present the control strategy of breakthrough drill bit during bone drilling process. The thrust force signal produced in the drilling process is the main source used to detect the breakthrough of the drill bit. From the force profile, it indicates a sharp drop in force during the intersection of drill bit between cortical and cancellous layer of the bone. However, there will be several peaks and troughs in the force profiles because of the variation of density throughout the bone. The fluctuation of the forces can affect the detection method to trigger a false event of breakthrough drill bit. Therefore, to avoid it from happening, the algorithm is design based on Equation (1) which is the difference the force values during the sharp drop.

$$F_{(z-1)} - F_z \geq F_t \tag{1}$$

The forces measured during the drilling process are in the tri-axial direction and denoted as force in the x-direction (F_x), y-direction (F_y) and z-direction (F_z). $F_{(z-1)}$ represents the previous force signal, whereas F_z is the current signal the F/T sensor measures. As in (1), the difference in the value of F_z is compared with the threshold force (F_t) obtained through preliminary drilling test. The suitable value of F_t is used in Equation (2) which is the complete algorithm for detection of breakthrough bone drilling process.

$$x_n = \begin{cases} x_i, & F_{(z-1)} - F_z \geq F_t \\ x_d, & F_{(z-1)} - F_z < F_t \end{cases} \tag{2}$$

In (2) x_n, x_i and x_d, are denoted as the current position, initial or safety position and desired position of the robot respectively. From the equation, it shows that when $F_{(z-1)}$ -F_z is greater or equal to the threshold value, the current position of the robot (x_n) will be equal to its initial position (x_i). Whereas if it is less than the threshold value, the current position of robot (x_n) will be equal to the desired robot position (x_d). x_i is the actual position for the robot to travel backward after the algorithm is triggered and x_d is the position of the robot to perform the drilling process.

Figure 2 shows the process cycle for the drilling operation. It begins with the setting up of the drilling parameters: velocity (v), acceleration (a), cutting speed, desired robot position (x_d) and robot initial position (x_i) on the track position. Then the operation mode needs to change during the drilling processes to activate the algorithm system. The F/T sensor measures the forces and torques produced during the drilling process. The measured data of F_z is then used in the algorithm to detect the breakthrough of the drill bit. If it triggers the event, the robot will stop the drilling process and return to its initial position. After the robot moves back to its initial position, the drilling parameters can be changed to perform other experiment. The process cycle ends if no other drilling process takes place.

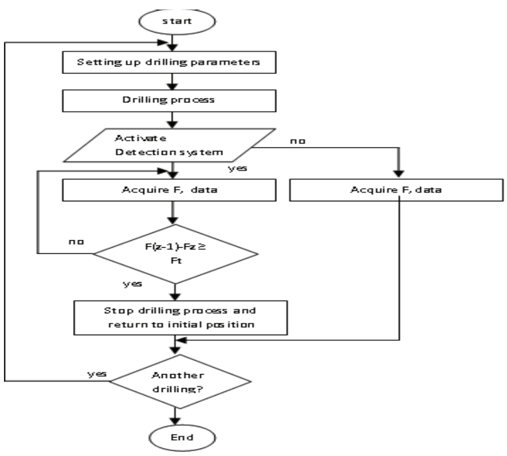
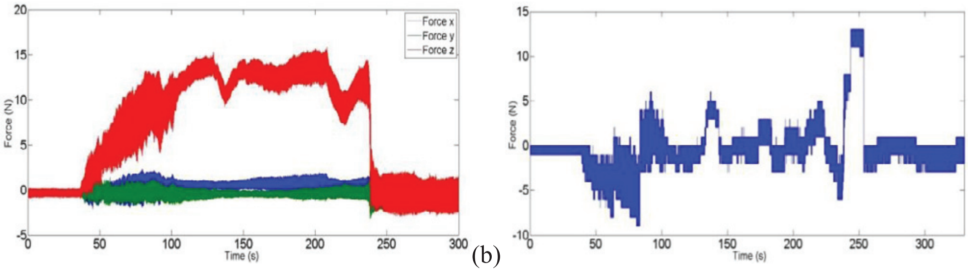


Fig. 3. Flow chart for breakthrough algorithm

5. Results and Discussion

The results represented are based on two different experiments: first experiment to calibrate and obtain the threshold force (F_t) while the second experiment to validate the breakthrough algorithm system. Four different graphs were obtained from each experiment, which consist of the measured forces in three different directions, measured feed rate (velocity and acceleration), measured different force values and measured track position (drilling depth). The data are plotted in graphical form against real time reading.

Figure 4(a) shows the forces profile for the preliminary drilling experiment with a velocity of 0.05 mm/s and acceleration of 0.0125 mm/s^2. The figure also shows that from 0 until 35 seconds, the drill bit tool is in the stage where no contact is made with the bone yet. Between the time intervals 20 to 240 seconds, the drill bit tool starts to penetrate the bone. The drilling process of the cortical bone can be observed and there are several peaks and troughs of forces in the z-direction (F_z) at time 137 seconds and 220 seconds. It penetrates the bone cortical layer into the cancellous layer after 240 seconds.



(a) (b)

Fig. 4. Measured (a) forces profiles (b) difference in the sharp drop force value for velocity of 0.05 mm/s and acceleration of 0.0125mm/s^2 during preliminary experiment

The different force value in the z-direction during the bone drilling process is shown in Figure 4(b). The figure shows the existence of four peaks at times 91, 137, 220 and 240 seconds with the measured forces at 6, 6, 5 and 13N respectively. This occurs because the bone properties differ in the overall density throughout the whole structure. Table 2 below shows the summary of the preliminary experimental results for two different parameters. Based on the results obtained, the value for the threshold force (F_t) is set approximately 11N. This is to ensure that the algorithm will not trigger a false signal during the event of breakthrough drill bit of the drilling process.

Table 1. Difference in the sharp drop force value

Feed rates		Force (N)
Velocity (mm/s)	Acceleration (mm/s^2)	
0.05	0.0125	13
0.06	0.015	12

The feedrate (velocity and acceleration) and measured track position (drilling depth) of the CRS robot are also observed during the drilling process as shown in Figure 5 during the preliminary drilling experiment using a velocity of 0.06 mm/s and acceleration of 0.015 mm/s^2. The CRS robot starts to move at 6 seconds from position 625 mm on the linear track and accelerates about 0.015 mm/s^2 until it reaches a velocity of 0.06 mm/s at 10 seconds. Then, the robot continues the drilling process in the cortical layer by maintaining the velocity until it reaches 200 seconds. At this state, it shows that jerk exists both in the measured acceleration, velocity and position profiles at about 17 seconds. As for the acceleration, the values increase and decrease between 0.015 mm/s^2 and -0.015 mm/s^2 during the time period and whereas velocity profile shows that the velocity of CRS robot starts to decelerate at -0.12 mm/s and accelerate back at 0.12 mm/s to achive a constant velocity of 0.06 mm/s. As for the robot position, a slight curve is formed at the same time period. This indicates that the intersection of the bone cortical and cancellous has occured. After the breakthrough of drill bit, the robot stops the movement on the track and the acceleratation and velocity decelerate at 243 seconds.

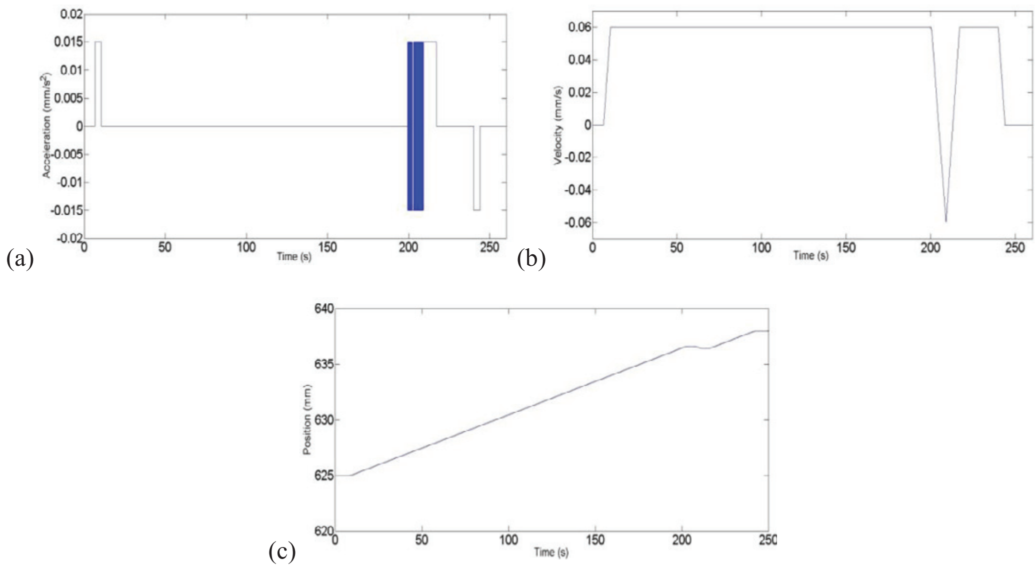


Fig. 5. Measured (a) acceleration (b) velocity (c) track position for velocity of 0.06 mm/s and acceleration of 0.015mm/s^2 during preliminary experiment

After the preliminary experiment test completed, the drilling process continued using the breakthrough algorithm system. The results of the tri-axial force and the difference in the sharp drop force for a velocity of 0.06 mm/s and acceleration of 0.015 mm/s^2 are shown in Figure 6. The figure also shows that from time interval 48 to 196 seconds, it indicates the state of drilling of the cortical bone and the value of the forces in the z-direction fluctuates. At time 196 seconds, it shows that the measured force in the z-direction value is 12.15N, which is already greater than the threshold force value of 11N. At this state, the breakthrough algorithm will be triggered and the CRS robot will stop the drilling process and return to the initial position (x_i). As shown in the figure, the value of the force in the z-direction is decreasing after 196 seconds and thereafter. After 347 seconds, it shows some increment of force indicating the retraction of the drill bit from the bone and no drilling process is taking place then.

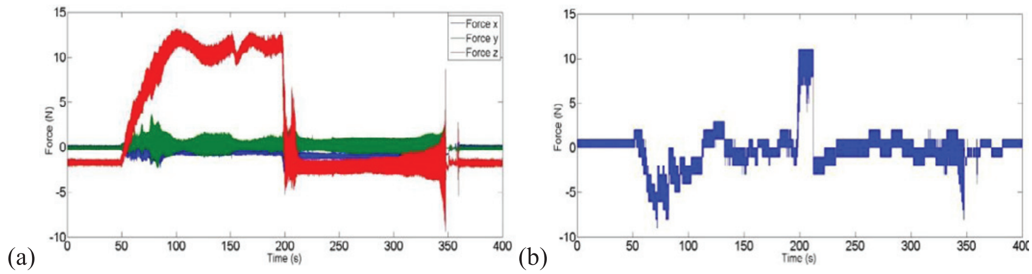


Fig. 6. Measured (a) forces profiles (b) difference in the sharp drop force value for velocity of 0.06 mm/s and acceleration of 0.015 mm/s^2

The movements and feed rates (velocity and acceleration) of the CRS robot after the breakthrough algorithm triggered are also recorded in Figure 7. In the figure, it shows that the robot starts to move from position 625mm on the track at 7.1 seconds with an acceleration and velocity of 0.015 mm/s^2 and 0.06 mm/s respectively. From the track position profiles, it shows the movement of CRS robot at constant velocity with the drilling depth increases about 11mm between 50 to 200 seconds. This indicates the drilling process of the cortical layer bone. After it reaches 636mm position on the track at 200 seconds, it shows that the drilling process has already penetrated the cortical layer. The moment the penetration occurs and the breakthrough algorithm detects the difference in the force value, as shown in Figure 6(b), system triggers. As a result, the CRS robot starts to reverse and moves towards the initial position (x_i). During this state, the velocity of the CRS robot decelerates at -0.06 mm/s with an acceleration of -0.015 mm/s^2 and maintains its speed until the robot reaches the initial position back to 625mm at 400 seconds.

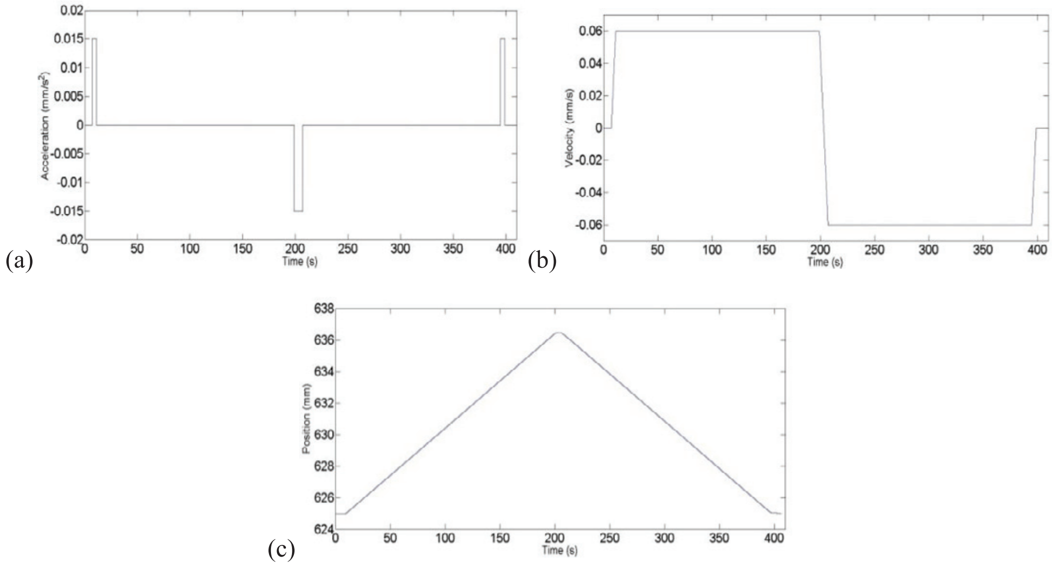


Fig. 6. Measured (a) acceleration (b) velocity (c) track position for velocity of 0.06 mm/s and acceleration of 0.015mm/s^2

6. Conclusion and Futurework

Many research projects have been conducted to illustrate the various kinds of detection methods for bone drilling processes. Researchers use various kinds of parameters as the threshold value for the breakthrough detection algorithm. In this research, the values of the tri-axial forces are measured. However, only the force value in the z-direction used as the threshold value for the detection algorithm and achieved through an experimental investigation using femur bone of a cow as the drilling specimen. The drilling operation was conducted using CRS Catalyst-5 robot controlled by a force-torque sensor architecture system. The breakthrough algorithm is built in the force-torque sensor architecture system. The experimental results showed that when the drill bit has penetrated or breakthrough the cortical layer into the cancellous layer, the difference in the force values during the sharp drop in the z-direction surpass the threshold value. The CRS Catalyst-5 robot will stop drilling and move to its initial position.

The detection method is important because it can help to increase the safety during the drilling process to prevent any drill bit breakage, unnecessary drill bit insertion and any mechanical damage to the bone or CRS Catalyst-5 robot itself. In the future, it is necessary to improve the research work by designing a new algorithm that can include other parameters such as the velocity, acceleration and cutting speeds to control the detection of breakthrough. In addition, the possibility of using a surgical drill bit to attain a more accurate result for drilling bone requires further research work.

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